

# **THE NEED FOR AND USE OF TECHNIQUES TO ASSESS THE MECHANICAL INTEGRITY OF TRANSFORMER WINDINGS**

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## **INTRODUCTION**

Power transformers are usually purchased with the expectation of satisfactory service lives of up to forty years. While under ideal circumstances lifetimes of forty years or more are being achieved, a variety of events or circumstances are causing much shorter terms. Various national and international studies have reported on failure rates and age [1, 2, 3]. A large proportion of transformer failures are a result of bushing and load tap changer malfunction or failure. Within the main tank, the key areas of concern relate to mechanical changes caused by short circuits, core ground issues and the various degradation processes associated with moisture levels in the paper, barriers, and oil. This paper looks at techniques that can help give confidence in the mechanical integrity of transformer windings.

## **NEED FOR ASSESSMENT**

Why is there a need to assess the mechanical integrity of windings?

This is a surprisingly simple question, but the answer is not obvious. To what extent would the knowledge reflect “a little learning is a dangerous thing”? Are there financial drivers that make the knowledge superfluous?

If we wish to assess the mechanical integrity, there is an implication that we are going to make a decision, probably relating to the use or life of a transformer, where knowledge of the mechanical integrity is relevant. Is it safe to return to service, after an incident, for example? What is the remaining life available within a particular transformer? Has there been any winding movement in transit?

These are simple questions that are also very difficult to answer definitively. Several tests are available to shed light on the issue of mechanical integrity. Some are already used routinely; others are less common [4].

Power factor and capacitance testing of bushings and winding insulation are, for many utilities, a routine off-line method of tracking dielectric deterioration. The power factor will also allow trending of winding moisture content, while the capacitance value will indicate gross movement and loss in core grounds.

Some power factor/capacitance units, such as the Doble M4000 Instrument, can also be used to measure other properties, such as those relating to the mechanical condition of the core and windings. These include turns ratio, exciting current and, with the M4110 module, the leakage reactance. This range of diagnostics collectively covers many of the key malfunctions occurring with the total transformer, many of which relate to mechanical integrity.

Within international groups, such as CIGRE Study Committee 12 [5] and the EuroDoble Clients Group [6,7], there has been interest over the last ten years in developing an additional test to focus upon mechanical problems, but to cover most of the malfunctions within this area. This method measures the transfer function of windings over a wide frequency range. While the approach being used started in North America [8], the greatest application has been in Europe. Many of the key technical papers have been presented by European clients and discussed at the Doble meetings during the 1990s [6, 7]. The view within Doble is that this method does have a role, and it is within the broad range of transformer condition assessment tools, providing corroborative evidence prior to an expensive consequential decision.

## DESIGN ISSUES

The technology assisting transformer designers has improved over recent years, but it is rare for the designs to be evaluated other than by subsequent service life. Short circuit tests need to be evaluated in terms of a test that can provide information about the effect of the tests, rather than simple survivability.

Further papers at this conference look at the area of transformer design.

Fingerprint testing of new transformers, whether for turns ration, leakage reactance or frequency response, provides a reference for the future.

Standards for short circuit testing of transformers usually specify leakage reactance/short circuit impedance. It involves a simple interpretation of a change in one value to another and is very suitable for a contractual use in a highly controlled environment. During factory acceptance the impedance is measured with three-phase excitation and high currents.

## FACTORY AND FIELD ISSUES

Once a unit has been involved in an 'incident', whether a through fault, a relay trip or a fault of some form, the ability to withstand further incidents is questionable.

It would make sense to have a set of tests available that include identification of possible damage, diagnosis of problems and prognosis for future development.

One approach is to rely upon an internal visual inspection, but it is almost invariably too difficult to draw effective conclusions. The oil has to be drained and confined entry rules apply. Since so little of the winding is visible, often little is seen other than displaced support blocks, which may have been there since commissioning.

Consequently, the reliance must be on condition assessment methods. However, since the consequences of an incorrect diagnosis are so great, a mandate is to have a range of complementary and effective diagnostic techniques available for field use.

Power transformers are specified to withstand the mechanical forces arising from both shipping and subsequent in-service short circuits across the terminals. The most severe service forces arise from close in system faults, faults in a load tap changer and, for a generator transformer, energizing out of synchronization. Short circuit forces produce axial and radial forces and these can lead to radial buckling or axial deformation (twisting, displacement of clamps or supports). Transport damage can occur if the clamping and restraints are inadequate, leading to core and winding movement. With a core form design, the principal forces are in the radial direction, while in a shell form design they are in an axial direction. This difference is likely to influence the types of damage found.

Condition assessment evaluation of transformers would be carried out on the following occasions:

- During an investigation, after a fault or protection trip. The purpose would be to determine the nature and extent of any damage.
- During a condition assessment. This test may done as part of a general assessment, or the unit may be known to have seen short circuits over time, and apparently successfully withstood them. In this latter case the test would be to identify possible damage and used to indicate the capability to withstand further short circuits.
- Before and after a relocation. Comparisons of test data made before and after a relocation, which should indicate any mechanical movement.
- By manufacturers as a quality check of the manufacturing process, by comparing the response of units made to the same design.

Testing is also carried out on new and refurbished units to obtain fingerprint values for references. Also, test results on sister units (similar design) can be used as references.

The result of such testing may have a number of implications:

- If the testing indicates damage or malfunction, and the test has been performed after operation of a protection relay - the unit is likely to need a major repair or scrapping. Further, confirmatory evidence may be necessary (e.g. additional testing specific to the type of fault indicated).
- If there is evidence of some damage or deformation, but there are no other signs of malfunction - the unit may possibly be returned to service. Engineering judgment is required to review the risk of failure at the next short circuit, the likelihood of such an event, and the system risk exposure. The results would be stored and used as a benchmark indicative of worsening of the damage.

Where there is no evidence of damage or deformation, and there is no other evidence (or expectation) of a malfunction - the unit is likely validated for service and the results archived for future use.

## **TOOLS TO ASSESS MECHANICAL INTEGRITY – INCLUDING LIMITATIONS**

In practice, when a unit is designated as requiring test and assessment, the following procedure would, in general, be pursued.

The transformer would be de-energized and all high voltage connections removed. The circuit and the transformer should be made safe for testing, according to standard company procedures. Ideally the transformer will have normal service oil in the tank. For the test program it is necessary to remove any temporary bushing ground connections. The leakage reactance and SFRA tests also require removing grounds from neutral bushings. A transformer with an off load tap changer would normally be tested in its normal operating position. A unit with a load tap changer would normally be tested with all taps connected, and preferably also re-tested with no taps in position.

The following test would provide evidence for evaluation.

### **Winding Capacitance**

The technique is capable of detecting gross winding movement.

### **Exciting (or Magnetizing) Currents**

This can be one of the simplest methods to detect shorted turns, following a short circuit [9].

### **Leakage Reactance/ Short Circuit Impedance**

Field measurements are usually single phase and at a low current. Experience indicates that an accuracy of around 0.2% is needed, to detect a 0.5% change over name-plate values. The success of the method relies upon the availability and reliability of factory data. In some cases a phase-by-phase comparison may assist in the analysis

### **Frequency Response Analysis**

There is a direct relationship between the geometric configuration of the winding and core and the series and parallel impedance network of inductance, capacitance and resistance. This network can be identified by its frequency-dependent transfer function. Frequency Response Analysis testing by the swept frequency method (SFRA) uses network analysis tools to determine the transfer function. Changes in the geometric configuration alter the impedance network, and in turn alter the transfer function. This enables a wide range of failure modes to be identified. Impulse FRA is also available.

Frequency Response Analysis is available in a number of versions, with varying repeatability and reliability.

## **FRA Variations In Test Technique**

Frequency response was developed initially by Dick and Erwin in the late 1970's in Canada [8].

The basis of the FRA technique is that the impedance of the transformer is a function of the resistance, inductance and capacitance. The impedance is also a function of the applied signal frequency. Consequently, the impedance at different frequencies relates to the resistance, inductance and capacitance of the winding. The resistance is clearly related to the physical construction of the winding – shorted turns etc would have an effect. Capacitance and inductance are related to the construction and geometry of the windings. Deformations and movements have an effect on both inductance and capacitance that may be reflected in the resulting frequency response.

Measuring the frequency response of a winding within a transformer, or of a transformer transfer function from winding to winding, gives a fingerprint for that winding or transformer. The measurement requires measurement of both input and output signals, which are then ratioed to give the response. This reduces the effect of the measurement system on the results. The resulting measurement system is, consequently, a three lead system involving input, measured input and measured response.

Measuring the frequency response may be performed by applying a simple varying frequency signal to the transformer that covers the frequency range of interest. This is the simple direct measurement.

An impulse method relies on indirect measurement of the frequency response. An impulse is applied to the winding that is under test. The impulse, or set of impulses, is assumed to consist of frequencies of interest. These frequencies are disentangled using signal analysis techniques to produce a frequency response plot. The technique is dependent on good impulse signals, fast signal processing and analysis.

A variation on the impulse technique is to use spectral techniques. This requires small impulses to be analyzed for particular frequency bands, which are then built into the final response. The technique should be less affected by noise, but will take more signals to build up a good response.

Both impulse and spectral techniques produce limited or poor responses at lower frequencies, up to a few hundred Hz, where there is much information to be gained about internal construction of the transformer in terms of inductance.

Tests in the UK in the subsequent decades showed that the swept frequency method had far higher repeatability over impulse methods.

Signals are applied and measured with respect to ground. The amplitudes and phases of the two signals, S Measurement and R Measurement, are measured to determine the relative amplitude and phase shift changes between them. The basic measurement is of the attenuation and phase shift of a signal after having passed through the winding from the input to the output terminal.

The test can also include voltage transfers between windings i.e. applying a signal to one winding of a transformer and measuring the response at another winding to determine the amplitude change and phase shift of the signal having been transferred along a winding, or from one winding to the other.

Early attempts to gain repeatability, particularly using impulse methods, were not successful. The success of the SFRA method is the result of a significant effort in developing a common protocol by EuroDoble Clients.

Doble uses the protocols developed by the EuroDoble Client Group. From this base, Doble has subsequently developed an instrument to match the requirements, the M5100 SFRA. The SFRA method is also comparative between phases and against previous results. There is also some commonality between units of the same design.

## **FRA INTERPRETATION**

A frequency response plot provides a fingerprint for a transformer. Fingerprints from similar transformers have common features.

Subsequent tests on a unit provide responses that may differ from the original due to both test set up and internal construction of the transformer itself.

Where there are differences between responses, a reason must be sought. Is it the test, or is it something within the transformer?

Much of the interpretation currently available is based on experience and subjectivity. This is because small variations may have large implications, and vice versa. Further, there are particular variations that are manufacturer specific which need to be extracted and examined in the light of experience. Some work has been done in statistical analysis of frequency response results, but little has been published, and nothing thus far relating to manufacturer specificity or the implications of small variations in responses.

The state of the transformer, in terms of magnetization of core, affects low frequency results. As disconnection of the transformer is unpredictable, there may be variation in these results. Experience has shown that these variations can usually be accounted for,

Impulse test techniques are prone to variation due to lead arrangement and impulse shape.

Swept frequency results (SFRA) have shown consistency between results between test teams, between test equipment and between results a number of years apart for many transformer types.

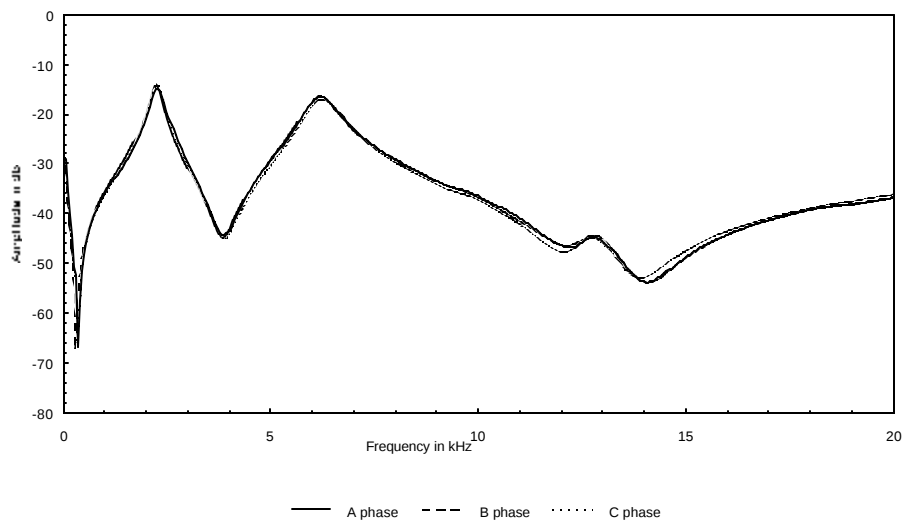
## **EXAMPLE RESULT AND APPLICATIONS AND INTERPRETATIONS**

While the application is now fairly straightforward, interpretation requires experience to diagnose the type of fault. Shown in Figure 1 is a typical set of results for an autotransformer in a sound condition. For most transformers there is a large attenuation at some low frequency, usually between 400 and 1500Hz. Below this the impedance is dominated by the series inductance and the 50-ohm measurement resistance. Since the impedance is controlled by the core magnetization, this is where core effects are seen and there is some equivalence with an excitation current measurement. The response of the center phase is slightly different in this area of frequency due to the different flux paths through the core. At the high attenuation frequency there is a phase change of 180 deg and the impedance changes from being inductively to capacitively controlled. At higher frequencies eddy currents shield the magnetic circuit and local leakage fluxes determine the winding inductances. The response is more dependent upon changes in the winding, and the diagnostics should compare with the leakage reactance measurements.

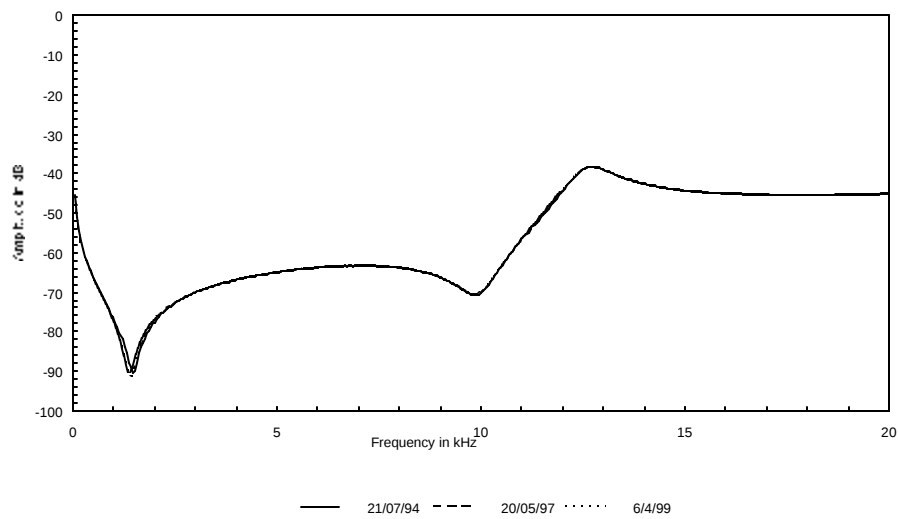
Figure 2 shows the results of three separate tests on a single generator step up unit. These tests were performed by different test teams, using different equipment, over a number of years.

Figure 3 shows the results from a damaged unit. Experience shows that differences in the lower frequency ranges relate to core changes, or shorted/open circuits. Medium frequencies show winding shifts, while more localised winding movement is seen at the higher frequencies.

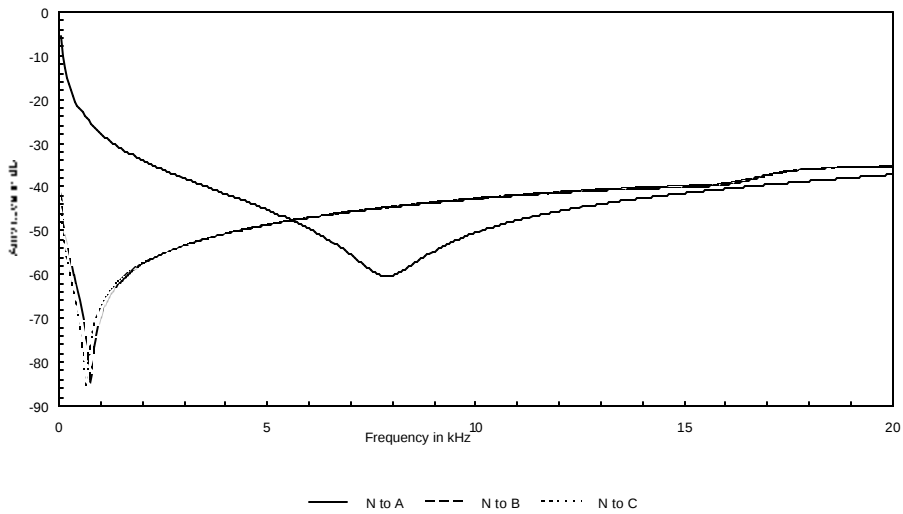
Figure 4 shows results from a test that might be thought to indicate a problem. However it was only by reference to similar plots on similar units that this response was shown to be normal. Equally, delta connected windings show differences, particularly at high frequencies. It is at this stage that experience and a significant dataset from designs of interest becomes important. It is also the indication that limitations with simplistic assessment programs appear.



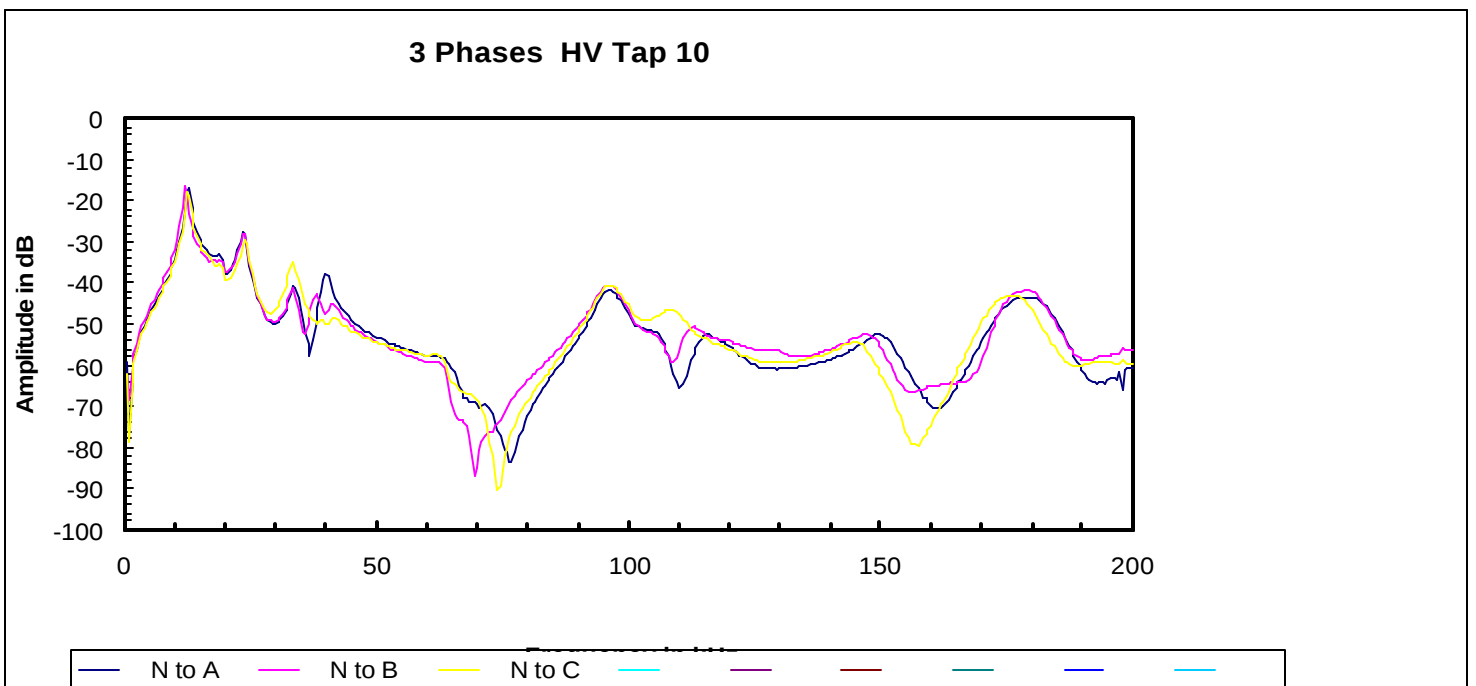
A Set of Normal Test Results from an Auto-Transformer  
**FIGURE 1**



Three Results For One Phase of One Transformer Taken Several Years Apart  
**FIGURE 2**



Test Results Indicating Shorted Windings  
**FIGURE 3**



Test results from a sound winding  
**FIGURE 4**

## CONCLUSIONS

A power transformer is one of the most critical items in a power system. It also has a very high capital value. In order to achieve the full benefit of this asset, it is important to have the most effective means of identifying any deterioration or malfunction. Visual inspections are not as effective as on other types of apparatus, such as circuit breakers, yet expensive decisions often have to be made relating to the future serviceability. This can only be achieved through the application of a broad range of complementary assessment tools. Within this context, Sweep Frequency Response Analysis with instruments such as the Doble M5100 SFRA has a valuable role.

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